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# PHOTOGRAPHIC INVESTIGATION OF LIQUID BEHAVIOR ON TEMPERATURE AND LIQUID-VAPOR SENSORS USED IN LOW-GRAVITY ENVIRONMENT

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# PHOTOGRAPHIC INVESTIGATION OF LIQUID BEHAVIOR ON TEMPERATURE AND LIQUID-VAPOR SENSORS USED IN LOW-GRAVITY ENVIRONMENT

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## SUMMARY

In developing the capability to restart a liquid-fueled rocket after a period of coasting in orbit, it is of prime importance to know the distribution of the propellant in the tank. Liquid-vapor sensors were installed in the liquid-hydrogen tank on an Atlas-Centaur rocket (AC-8) to aid in determining the location of the propellant. Since such sensors could be subject to erroneous liquid indications because of bulk liquid clinging to the sensing tip even in a vapor environment, an experimental laboratory study of the sensing tip was conducted under simulated coasting flight conditions.

The results of the investigation indicate that surface tension will cause a wetting liquid to migrate in the direction of increasing radius on a conical surface when in a zero-gravity environment. The sensor should be mounted in such a position that any system acceleration would also cause liquid to move in the direction of increasing radius. These two forces, surface tension and acceleration, would then combine to prevent any collection of liquid on the sensing tip of the cone. Also, any abrupt discontinuities on the surface will act as liquid collectors.

## INTRODUCTION

The Atlas-Centaur research and development program included three flights that were designed to demonstrate restart capability of the Centaur stage following a coasting period in Earth orbit. Pressure buildup resulting from thermal energy inputs during this period required the venting of the liquid-hydrogen tank. The ullage must therefore be positioned over the vent entrance located in the forward end of the tank to avoid liquid-propellant losses and severe vehicle-attitude-control problems resulting from liquid expulsion. Also, at the termination of the coasting phase of the flight, engine restart demands that the liquid hydrogen be positioned at the outlet line near the tank bottom. The

failure of the AC-4 flight to restart after a coasting period provided dramatic illustration of these coasting phase propellant management problems (ref. 1).

Several important design changes were incorporated into the AC-8, the next two-burn flight in the development series. These changes, documented in reference 2, were necessary to eliminate the propellant problems encountered on the AC-4. One change was the uprating of an auxiliary thrust system, varying from 6 to 100 pounds during the coasting phase of the flight. This auxiliary thrust resulted in a positive acceleration, relative to Earth gravity, to gain and maintain control of the propellant. To determine the effectiveness of these changes and to assure knowledge of the location of the liquid hydrogen and its vapor during the coasting period, the interior of the Centaur fuel tank was instrumented with liquid-vapor sensors and temperature sensors. The sensors were mounted on the supporting structures shown in figure 1.

In a low-gravity environment, a wetting liquid (contact angle  $<90^\circ$ ) normally clings to a surface because of the force of surface tension, and thus renders sensors designed for Earth environment inoperative. The sensors used in the AC-8 were conically shaped to utilize the force of surface tension to uncover the sensing tip.

Related works in this field, both experimental and analytical, deal with liquid configuration inside objects such as tanks, tubes, etc. (refs. 3 to 6). Reference 6 deals with the stability of a liquid inside a tapered tube. The result shows that, in low-gravity environment (surface-tension force much greater than gravity force), wetting liquid inside a tapered tube moves toward the smaller diameter. There are no published data on liquid configuration on the external surface of objects in a zero- or low-gravity environment.

To verify the design concept of the sensor and to determine a preferred orientation of the sensor, if any, with respect to the liquid surface, tests were conducted at the Lewis Research Center zero-gravity drop tower facilities. The results of the investigation are reported herein.

## APPARATUS AND PROCEDURE

### Test Facility

The Lewis 100-foot drop tower is shown schematically in figure 2. The experiment package was suspended from the top of the tower and dropped to the first floor, where it was decelerated in a 7-foot-deep bed of sand. The drop distance was 85 feet, and the resulting weightless time was 2.25 seconds. In zero-gravity tests, air drag was kept to a minimum (below  $10^{-5}$  g) by allowing the experiment to free fall inside an air-drag shield. For the low-gravity tests, the experiment package was attached to the inside



bottom of the drag shield. This procedure resulted in a variable gravity field (because of air drag) during the drop, beginning at less than  $10^{-5}$  g and increasing to  $10^{-2}$  g just prior to impact in the sand box. A complete description of the test facility is given in reference 5.

## Experiment Tank, Test Sensors, and Test Liquids

The cylindrical experiment tank used in this investigation and shown in figure 3(a) was machined from a transparent acrylic block. The tank had an inside diameter of 8.5 inches, a wall thickness of 0.75 inch, and a height of 10 inches. The flat top and bottom covers were fabricated from clear plastic and stainless steel, respectively, and sealed with O-rings to sustain pressure in the tank. A circular plastic baffle plate, 0.25 inch thick and 6 inches in diameter, was attached 1 inch down from the top of the tank to prevent the incoming pressurizing air from impinging directly on the sensor. A second baffle plate was attached 1 inch up from the tank bottom and centered over the tank outlet. Two types of disk were used for the bottom baffle plate: a plain disk and a disk with three small holes drilled through it. The experiment tank mounted on the experiment package is shown in figures 3(b) and (c).

The liquid-vapor sensor and the temperature sensor are shown in figures 4(a) and (b), respectively. The sensors used in this investigation, shown schematically in figures 4(c) to (e), were full-scale models of the flight sensors and were fabricated from either clear acrylic or opaque white plastic. The model temperature sensor with a simulated wire lead protruding from the conical portion of the sensor is shown in figure 4(e). The protuberance was the result of adding a conical insulating body to the conical sensing tip. The addition of the insulating body was not contemplated in the original design. The sensor was mounted inside the experiment tank on a clear plastic rod, as shown in figure 3(a). The sensor could be mounted either in the horizontal position, as shown, or vertically from either the top or bottom plate.

The liquids used in this investigation were 200-proof ethanol and trichlorotrifluoroethane (Freon), the physical properties of which are given in table I. Ethanol was used because its kinematic surface tension is similar to that of liquid hydrogen used in the Centaur. The similarity in kinematic surface tension permits a direct simulation of the Bond number (ratio of gravity force to surface-tension force) and, therefore, a direct simulation of the low-gravity environment. Furthermore, ethanol is a wetting liquid on most solids and its contact angle on plastic is nearly zero degrees; thus, it simulates the contact angle of liquid hydrogen on the actual flight sensor material. Trichlorotrifluoroethane was used to observe the effect of viscosity, if any, on the sensor performance. Small amounts of methylene blue dye and Sudan IV red dye were added to ethanol and

Freon, respectively, in order to improve the visual observation of the liquids on the probe when viewed on the data film. The addition of the dye had no measurable effect on the physical properties of the liquids.

## Experiment Package

The experiment tank used in this study was mounted in the experiment package, as shown in figures 3(b) and (c), and suitably illuminated to permit high-speed photography of the test sensor during the test drop with a 16-millimeter motion picture camera. The camera was equipped with either a 25-, 35-, or 102-millimeter lens to facilitate various degrees of closeup views of the test sensor. All electrical power required for the experiment was carried on the experiment package and consisted of rechargeable nickel-cadmium cells. An electrical solenoid valve controlled a small air piston that opened the tank outlet at the beginning of the drop test and closed the outlet by a timed relay after a predetermined time period.

Air pressure supplied to the top of the tank through stainless-steel tubing expelled the liquid from the tank when the outlet valve was opened. The air was contained in pressure bottles, pressurized to 120 pounds per square inch gage, and regulated to 25 pounds per square inch gage in the clear plastic tank by means of two pressure regulators. The air was passed through a commercial air filter during the pressurizing process.

## Test Procedure

The test tank and associated hardware required for filling the tank with liquid were cleaned prior to each test with a detergent-water solution and then ultrasonically treated, in order to preserve surface-tension values and contact angles of the liquids on all surfaces. The tank, with the sensor mounted in the desired position and with the proper outlet baffle, was then assembled and mounted in the experiment package.

With the outlet solenoid valve closed, the tank was filled with the test liquid to the desired depth. The system was then sealed and pressurized.

The experiment package was then statically balanced about the vertical geometric axis by adding small brass weights where required. After placing the package in the air-drag shield, the assembly was hoisted to the eighth floor and hung in the predrop position on a length of music wire. The music wire was then severed and the drag shield and experiment package were allowed to free fall.

The two different types of outlet baffles, as shown in figure 3(a), permitted two different methods of wetting the test sensor with liquid. With the plain circular outlet baffle, the tank was filled with test liquid to a depth which completely submerged the conical portion of the sensor. At the start of the test drop, the outlet valve was opened, and liq-

uid was expelled from the tank, uncovering the test sensor. After 1.5 seconds of liquid expulsion from the tank, the outlet valve was closed. The outlet baffle permitted maximum liquid expulsion from the tank and prevented any backsplash of liquid into the tank when the outlet valve was closed.

The second type of test utilized the outlet baffle with three holes. Prior to the drop, the tank was filled with about 2 inches of liquid, so that the sensor would be in vapor. Liquid expulsion was initiated at the inception of the drop, continued for 0.25 second, and then stopped. The closing of the outlet valve resulted in a backsplash, and streams of liquid directed at the test sensor were emitted from the three holes in the baffle plate. The resulting contact and wetting of the sensor was visually recorded on the data film.

## RESULTS AND DISCUSSION

The experimental results of the drop-tower tests are presented in the form of selected photographs taken from motion picture film. The tests conducted are listed in table II. In general, the tests confirmed the soundness of the design concept. During low-gravity conditions, when surface tension predominates, residual liquid on a conical surface is in a state of nonequilibrium. The surface-tension force causes the residual liquid to move in the direction of increasing cone radius until it reaches the cylindrical portion, where equilibrium is restored. An analytical derivation of the nonequilibrium condition is presented in the appendix.

The sensors were subjected to two types of wetting. A cyclical wet-dry sequence, as may be expected when the fluid is sloshing, was simulated by the draining test. Random splash wetting, for comparative purposes, was simulated by a splash test. These tests are described under Test Procedure in the preceding section.

### Draining Test

Figure 5 shows the typical effect of sensor orientation during draining tests. The vertical upright orientation, shown in figure 5(a), is preferred because the gravity force and the surface-tension force add vertically and result in a minimum amount of liquid wetting of the sensor. In figure 5(b), the gravity force opposes the surface-tension force, and thus reduces the effect of the surface-tension force in removing the residual liquid from the tip. In the orientation shown in figure 5(c), the liquid has a tendency to collect on the lower horizontal axis. However, the sensing tip remains free of liquid.

The liquid-vapor sensor mounted in a horizontal position is shown in figure 6. In this orientation, a sheet of liquid adheres to the sensor body after the liquid level has passed the sensor. In figure 6(d), liquid can be seen falling from only the cylindrical body under

the force of impact at the termination of the free-fall period. This figure illustrates that the conical tip is free of residual liquid during the latter portion of the free-fall period.

The sensor mounted in a vertical upright position is shown in figure 7. The sensing tip is readily uncovered as the liquid level drops. Surface-tension effects on the sensor in this orientation are minimal. Figure 8 shows the sensor mounted in a vertical downward orientation. These figures are typical time sequences to show the effect of surface tension, as discussed previously. In this orientation, the liquid tended to cling to the sensing tip. In figure 8(d), a ring of residual liquid can be seen near the sensor tip. In the motion picture film, the ring was seen traveling upwards toward the cone-cylinder junction.

The configuration of the liquid on the temperature sensor, with a wire lead extending from the sensor tip, is illustrated in figure 9. Figures 9(a) and (b) show liquid clinging between the protuberance and the sensor body. Fortunately, the sensing tip is again free of residual liquid. It is believed that the residual liquid between the protuberance and the body is in the form of an unstable thin film. Any disturbance would cause the film to break. In another test (figs. 9(c) and (d)), the liquid level at the start of the test did not cover the protuberance entirely. In this case, there was no residual film formation, as is confirmed in figure 9(d), where liquid is shown to be falling from the main body but not from the sensing tip. The liquid drained in much the same fashion as it did on liquid-vapor sensors which have no protuberances (fig. 6).

## Splash Test

A splash sequence with a temperature sensor is shown in figure 10 and illustrates the splash test method. The experiment tank was filled with about 2 inches of liquid, and the sensor was thus left in vapor. The tank was drained for 0.25 second at the inception of the drop, and then the valve was closed. This method of draining resulted in a back-splash, and streams of liquid were emitted from the holes in the baffle plate and directed at the test sensor (figs. 10(a) and (b)). The photographs shown in figures 10(b) and (c) were taken approximately 2 seconds apart and show that the liquid traveled away from the tapered portion of the sensor. The last photograph of the sequence (fig. 10(f)) shows the liquid falling from the sensor under the force of impact. Again it can be seen that the majority of the liquid moved away from the tip. This phenomenon is also shown in figure 11. Figure 11(a) shows the temperature sensor evenly covered with residual liquid immediately after being splashed. Figure 11(b) shows liquid collected away from the sensing tip approximately 2 seconds after the drop began. Figures 11(c) and (d) are closeup photographs of the model liquid-vapor sensor. The shaded region of the sensors indicates the residual liquid. It can be seen in figure 11(d) that most of the residual liquid moved away from the tapered sensing tip.

A liquid-vapor sensor mounted in a horizontal position and splashed with Freon is shown in figure 12. Figure 6 illustrates the same sensor similarly mounted in a draining test with ethanol. Comparison of these photographs shows that the results are very similar. Figures 12(e) and 6(d) show that, when the drop is terminated, most of the residual liquid is falling from the body of the sensor; thus, the sensing portion of the sensor is not wetted during the latter portion of the drop.

From the photographs presented, it was concluded that the preferred orientation in the tests is with the sensor in the vertical upward position. In this orientation, the gravity force acts in the same direction as the surface-tension force and thus aids the liquid-film movement away from the sensing tip. Mounting the sensor horizontally is acceptable, but the gravity force does not aid in the liquid movement. The least desirable orientation of the sensor is in the vertical downward position. In this orientation, surface tension caused the bulk liquid to cling to the sensing tip, which could result in erroneous indications.

Most of the sensors on the Centaur vehicle were installed in the vertical upward orientation in order to take advantage of whatever acceleration field was available. Sensors on the vertical strut, however, were mounted horizontally for ease of installation. As shown in the photographs presented here, with these orientations, residual liquid will not cling to the sensing tip under a low-gravity environment.

## CONCLUSIONS

The effect of surface tension on a cone-shaped sensor when in a low-gravity or zero-gravity environment was investigated. The qualitative results of this investigation indicate that a wetting liquid on a conical surface moves in the direction of increasing radius because of surface tension.

During the drop test, the conical portion of the sensor was cleared of residual liquid within the 2-second period of low-gravity environment available in the drop tower. The residual liquid moved away from the sensing tip within this time. The test photographs show that the residual liquid will not cling to the sensing tips and render them inoperative.

Any protuberance will act as a liquid collector; however, the liquid film formed between protuberances and the sensor body on the model tested appeared to be unstable and would break away under minor disturbances. Nevertheless, these protuberances should be avoided in any design wherever possible.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, March 21, 1967,  
891-01-00-06-22.

## APPENDIX - ANALYTICAL DERIVATION OF LIQUID MOTION ON CONICAL SURFACE UNDER LOW GRAVITY

The direction of liquid motion on a cone-shaped object can be derived from a pressure difference consideration. The pressure difference at the point of intersection of the cone and liquid ring (fig. 13) is

$$P_2 - P_o = \sigma \left( \frac{1}{r_2} + \frac{1}{R_2} \right) \quad (1)$$

where  $P_2$  is the internal pressure of the liquid ring at point 2,  $P_o$  is the ambient pressure,  $\sigma$  is the surface tension of the fluid,  $r_2$  is the radius of the cone at point 2, and  $R_2$  is the principal radius of curvature. At cone radius equal to  $r_1$ , the pressure difference is

$$P_1 - P_o = \sigma \left( \frac{1}{r_1} + \frac{1}{R_1} \right) \quad (2)$$

where  $P_1$  and  $r_1$  are internal pressure and the radius of the cone, respectively, at point 1. When equation (2) is subtracted from equation (1), and neglecting  $1/R_1$  and  $1/R_2$ , since  $R_1$  and  $R_2$  are  $\gg r_1$  and  $r_2$ , the result is

$$P_2 - P_1 = \sigma \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \quad (3)$$

From figure 3, it can be seen that  $r_1 > r_2$

$$\therefore P_2 - P_1 = \sigma \left( \frac{1}{r_2} - \frac{1}{r_1} \right) > 0 \quad (4)$$

Therefore, since the pressure gradient from point 2 to point 1 is positive, the liquid will flow toward point 1 (i.e., in the direction of increasing radius).

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4. Nussle, Ralph C.; Derdul, Joseph D.; and Petrash, Donald A.: Photographic Study of Propellant Outflow from a Cylindrical Tank During Weightlessness. NASA TN D-2572, 1965.
5. Petrash, Donald A.; Zappa, Robert F.; and Otto, Edward W.: Experimental Study of the Effects of Weightlessness on the Configuration of Mercury and Alcohol in Spherical Tanks. NASA TN D-1197, 1962.
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TABLE I. - PROPERTIES OF LIQUIDS

Liquid	Temperature, °C	Viscosity, cP	Density, g/cm <sup>3</sup>	Surface tension, dynes/cm	Kinematic surface tension, cm <sup>3</sup> /sec <sup>2</sup>
Ethanol	20	1.22	0.789	22.5	28
Freon	20	.7	1.6	18	11.25
Hydrogen	-254	.00016	.0718	2.37	33

TABLE II. - TEST CONDITIONS

Run	Sensor type and orientation (a)	Test liquid	Gravity field	Test model material	Type of test	Type of lens, mm
1	L-1	Ethanol	Low	Clear plastic	Draining	35
2	L-2	↓	↓	Clear plastic	↓	↓
3	L-3	↓	↓	Clear plastic	↓	↓
4	L-3	↓	↓	Opaque white plastic	↓	↓
5	L-2	↓	↓	Opaque white plastic	Splash	102
6	L-1	Freon	↓	Clear plastic	Draining	35
7	T-2	Ethanol	↓	Opaque white plastic	Splash	35
8	L-2	Ethanol	Zero	Clear plastic	↓	102
9	T-2	Ethanol	Zero	↓	↓	35
10	L-2	Freon	Low	↓	↓	↓
11	T-2	Freon	↓	↓	↓	↓
12	T-2D	Ethanol	↓	↓	Draining	↓
13	T-2U	Ethanol	↓	↓	Draining	↓

<sup>a</sup>Liquid-vapor sensor in orientation 1 (vertical, tip facing down), L-1; liquid-vapor sensor in orientation 2 (horizontal), L-2; liquid-vapor sensor in orientation 3 (vertical, tip facing up), L-3; temperature sensor in orientation 2 (horizontal), T-2; temperature sensor in orientation 2D (horizontal, wire lead facing down), T-2D; temperature sensor in orientation 2U (horizontal, wire lead facing up), T-2U.



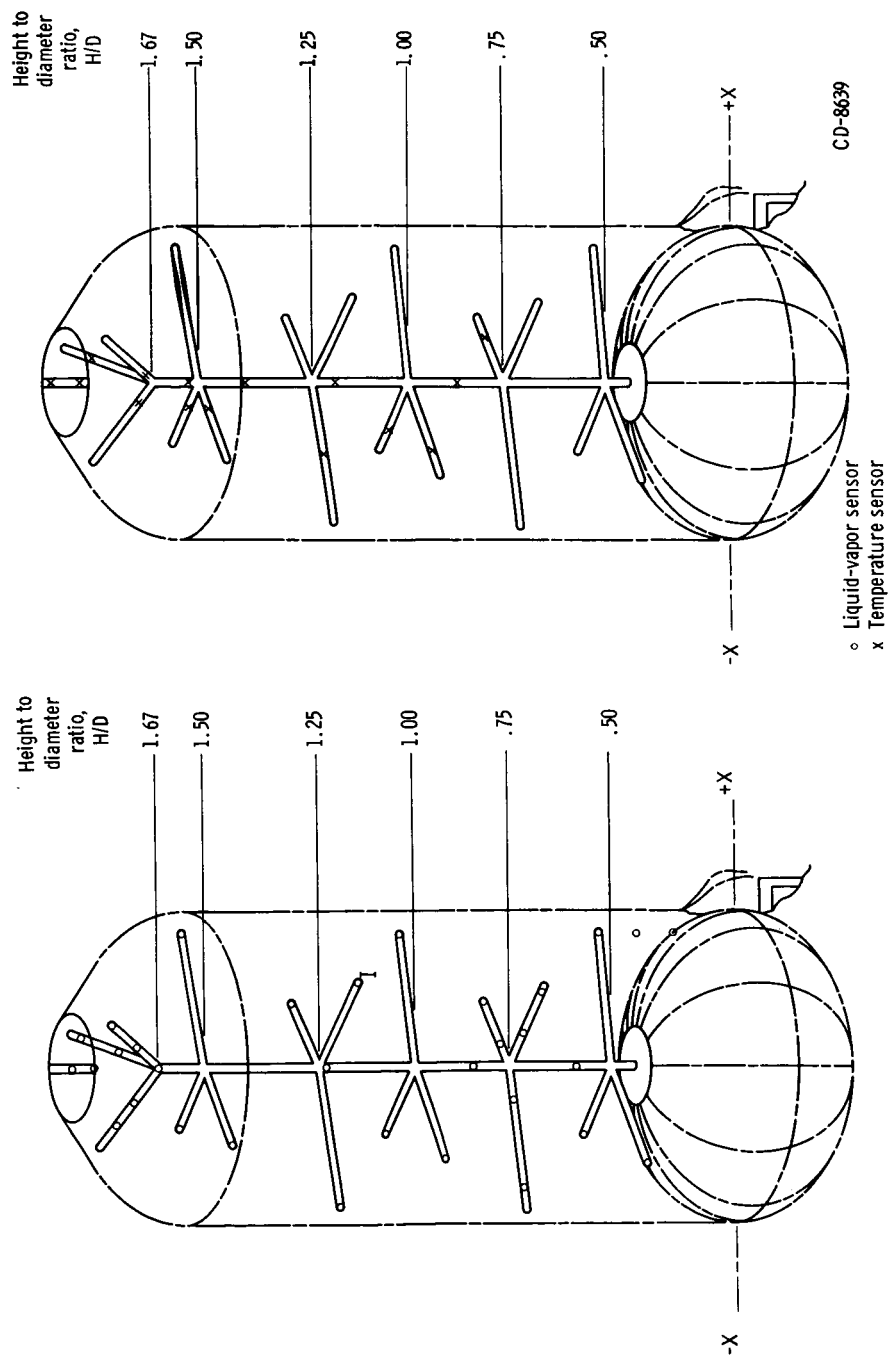
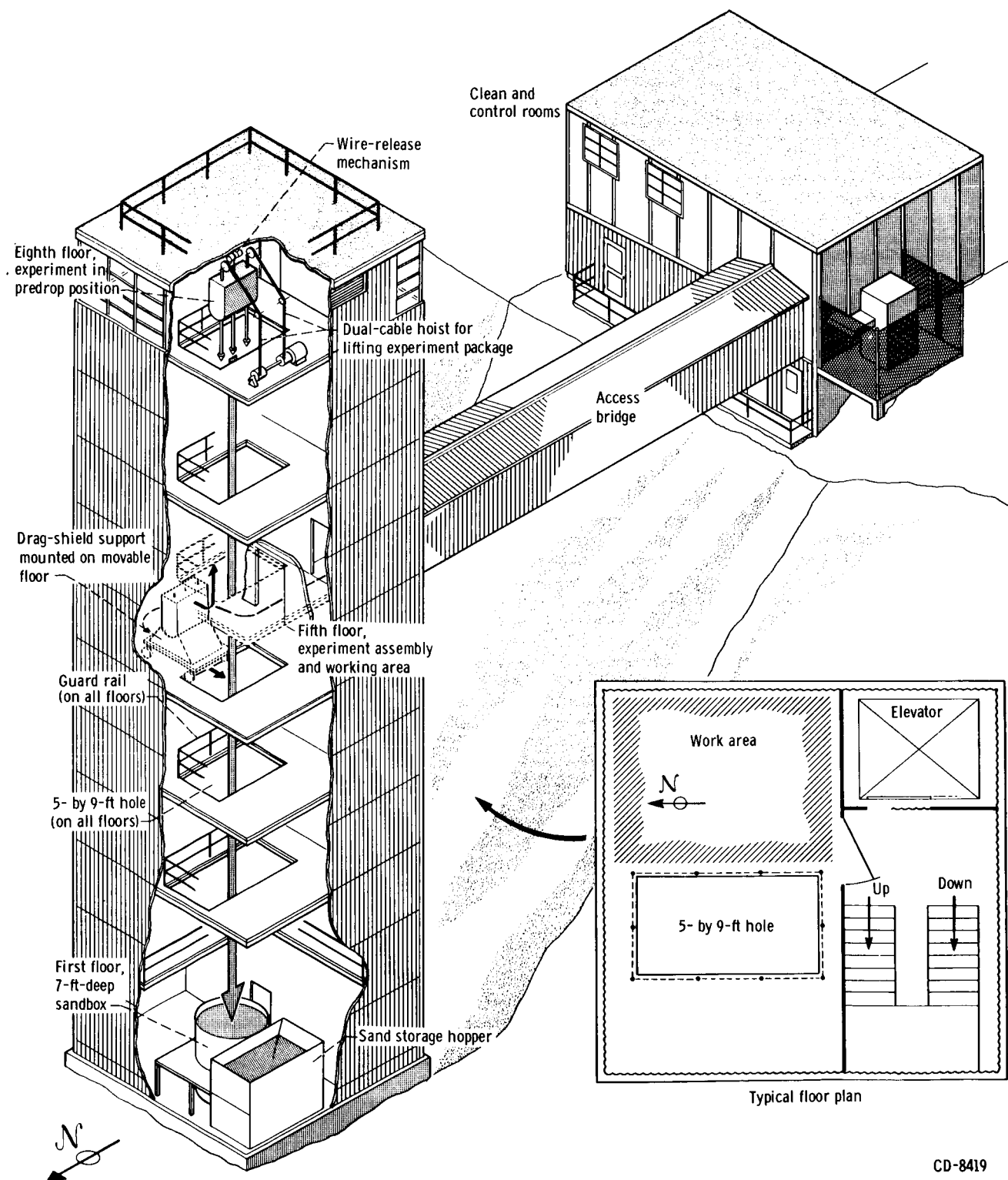
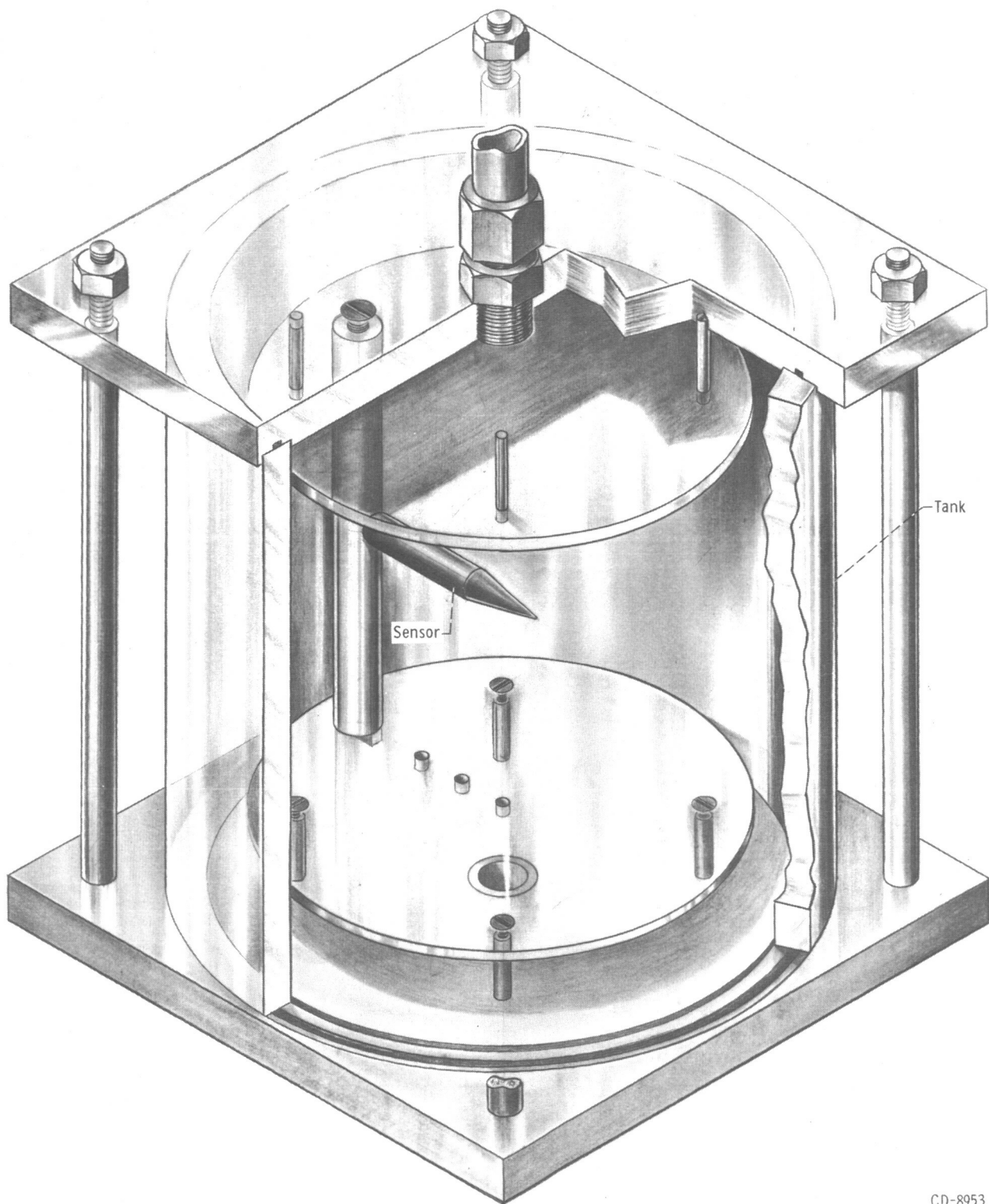


Figure 1. - Liquid-vapor sensor and ullage-gas temperature instrumentation in Centaur liquid-hydrogen tank. Diameter, 10 feet.



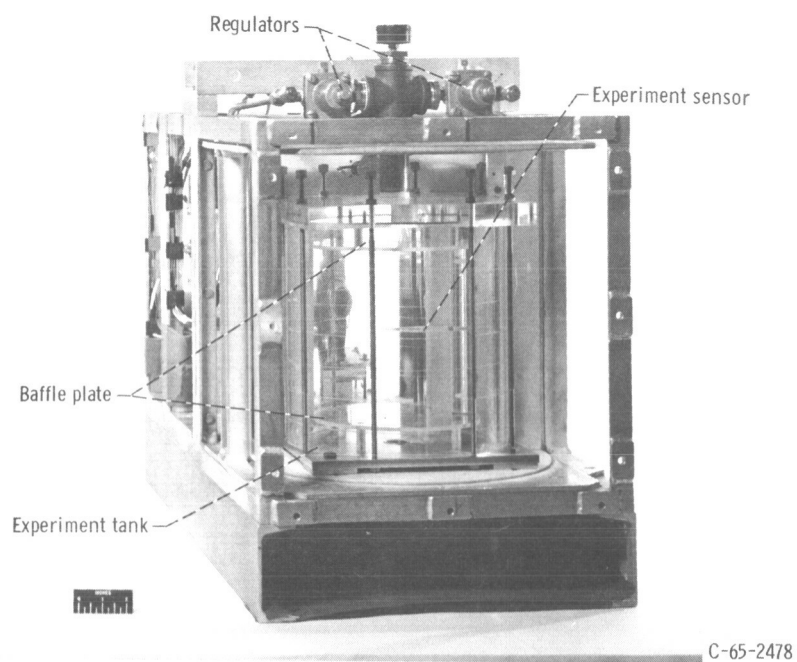
CD-8419



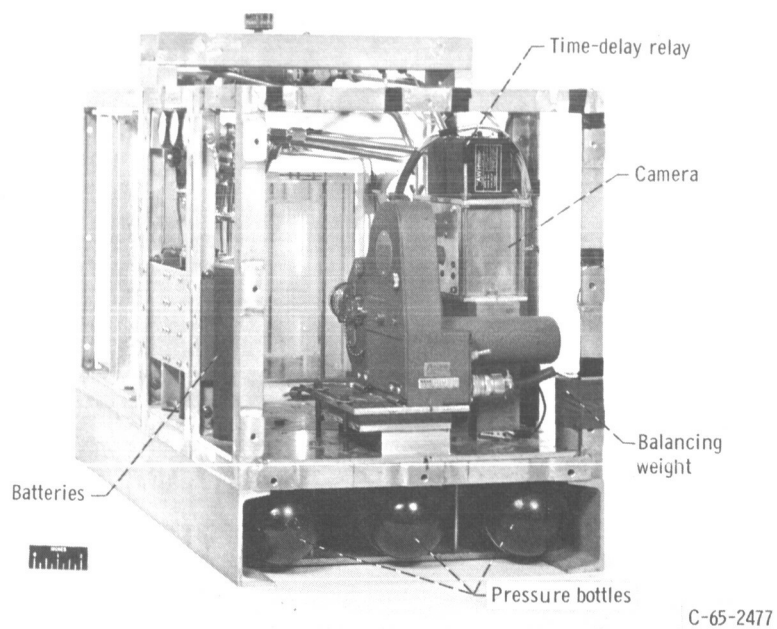
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(a) Experiment tank and sensor.

Figure 3. - Apparatus.

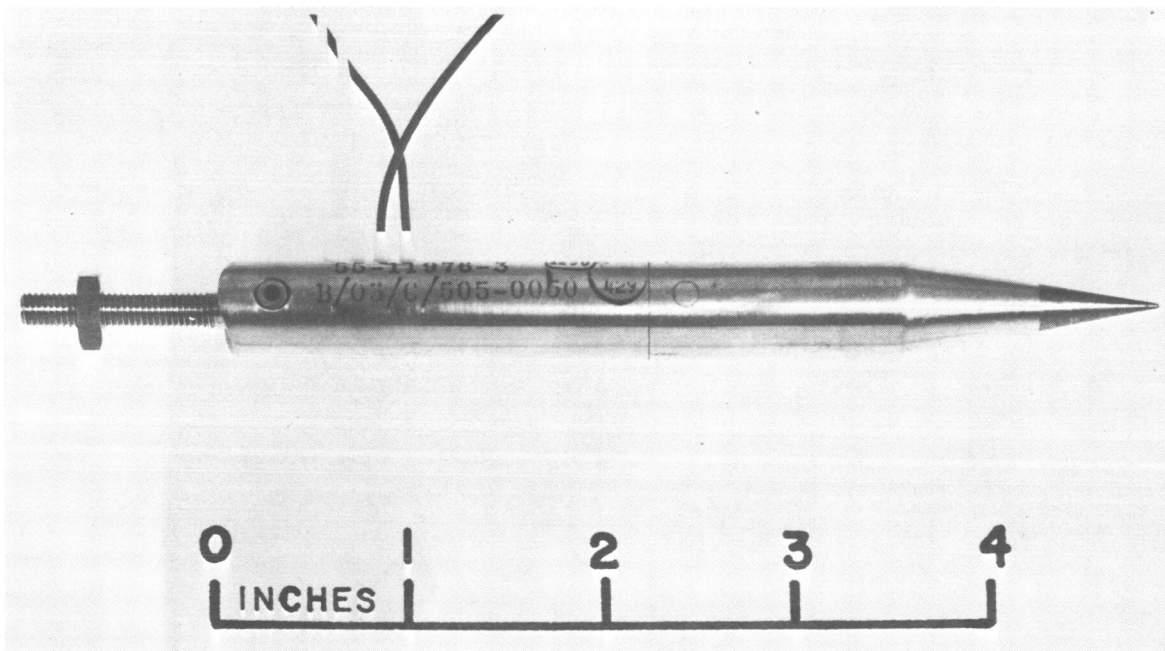


(b) View of experiment package showing sensor test model.

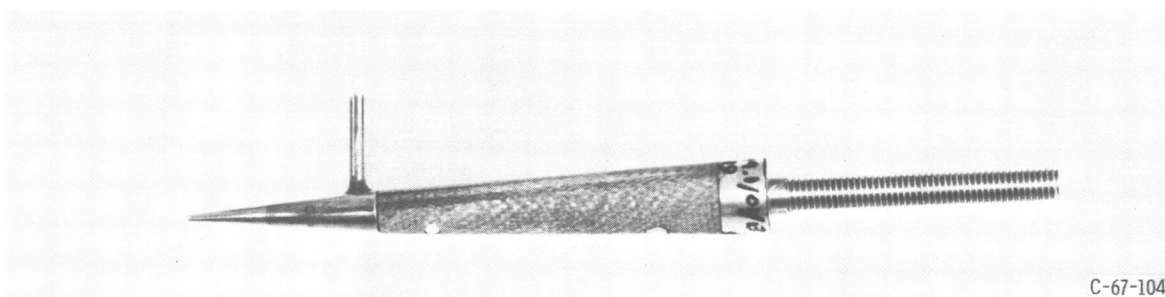


(c) View of experiment package showing camera.

Figure 3. - Concluded.



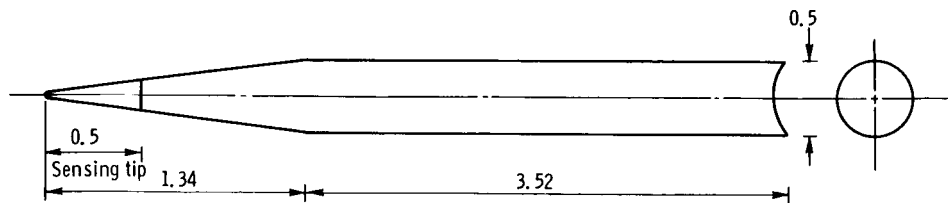
(a) Liquid-vapor sensor, flight model.



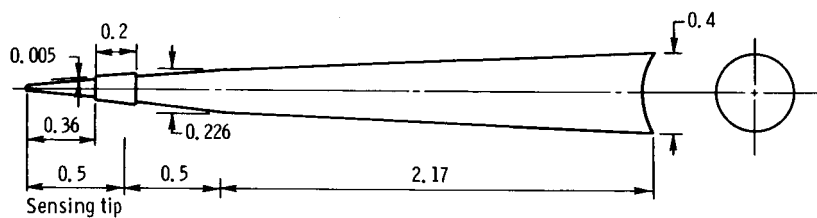
C-67-1048

(b) Temperature sensor, flight model.

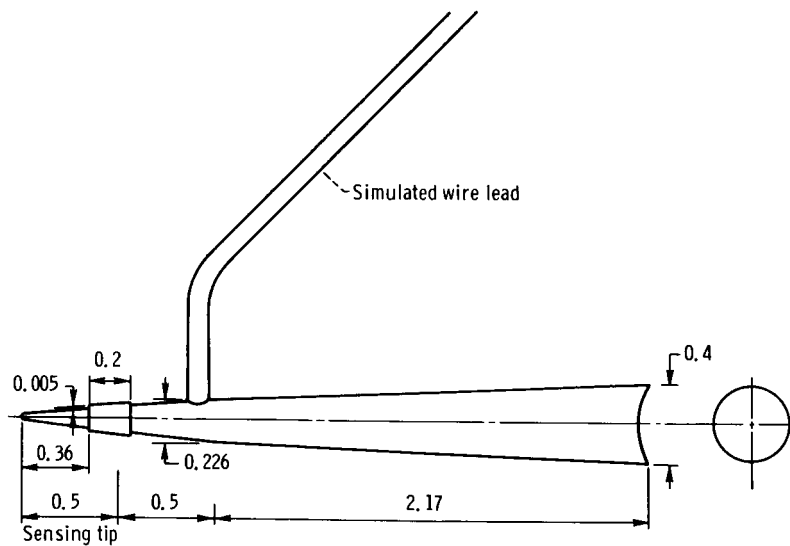
Figure 4. - Sensors.



(c) Liquid-vapor sensor, test model. (Dimensions are in inches.)

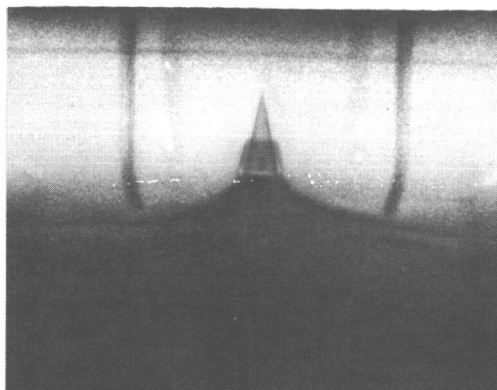


(d) Temperature sensor, test model. (Dimensions are in inches.)

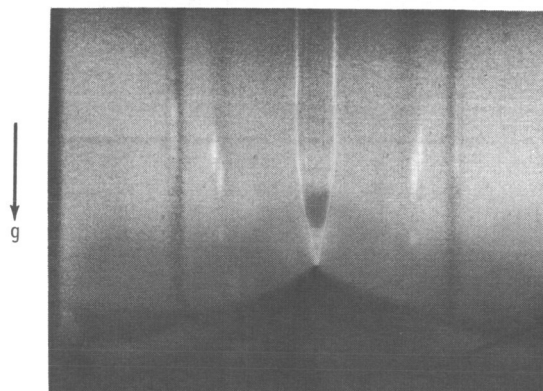


(e) Temperature sensor with simulated wire lead, test model. (Dimensions are in inches.)

Figure 4. - Concluded.



(a) Sensor in vertical upward orientation.

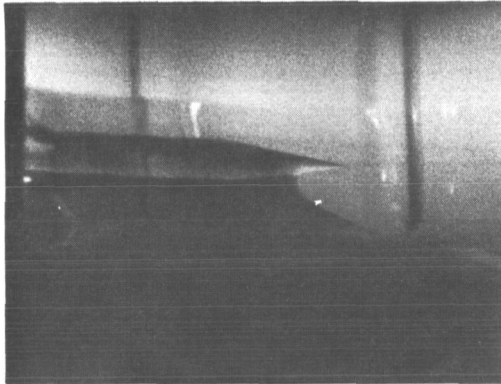


(b) Sensor in vertical downward orientation.

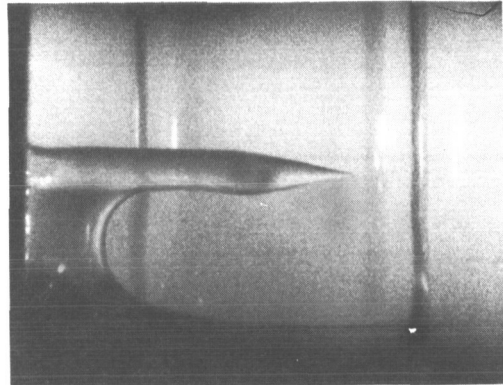


(c) Sensor in horizontal orientation.

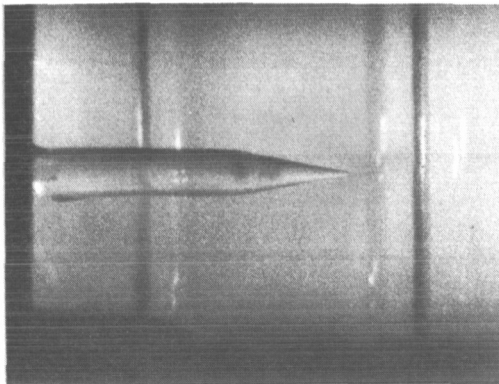
Figure 5. - Uncovering of liquid-vapor sensor as affected by sensor orientation. Draining test in ethanol.



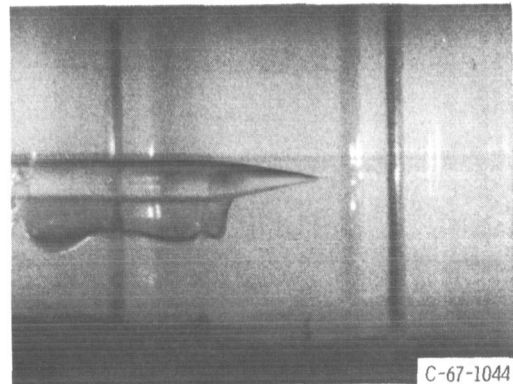
(a) Sensor 90 percent covered.



(b) Sensor 20 percent covered.



(c) Thin film on sensor.



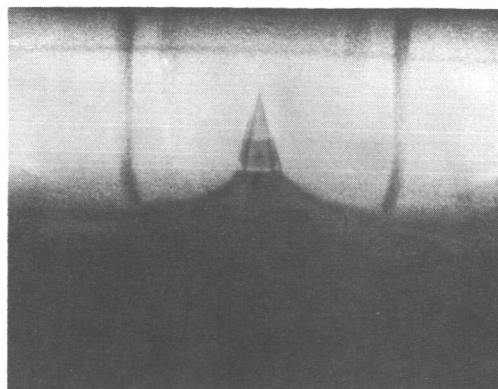
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(d) Termination of drop; residual liquid falling from sensor body only.

↓  
g

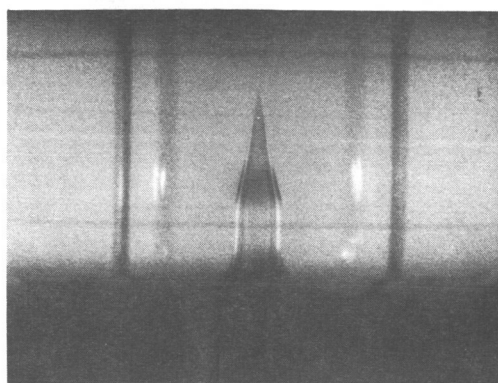
Figure 6. - Uncovering of liquid-vapor sensor in horizontal orientation. Draining test in ethanol.



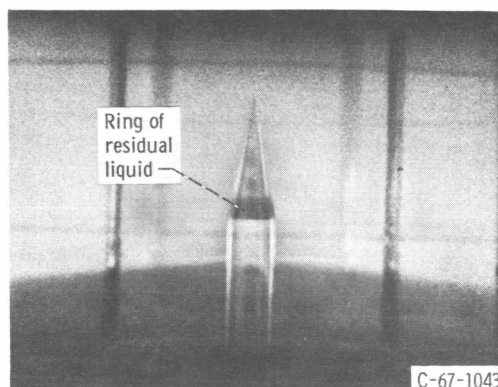


(a) Sensor tip uncovered.

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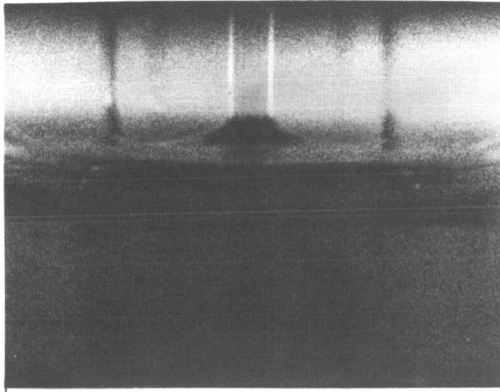
(b) Residual liquid collecting at interface.



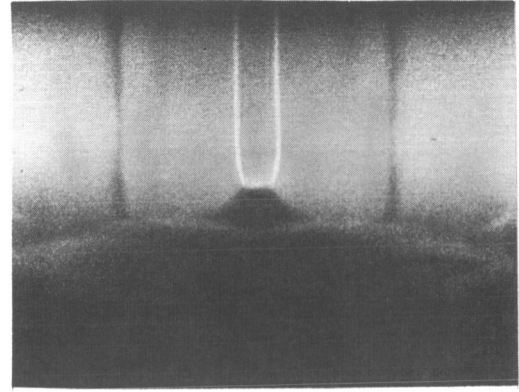
C-67-1043

(c) Residual liquid band formed at interface.

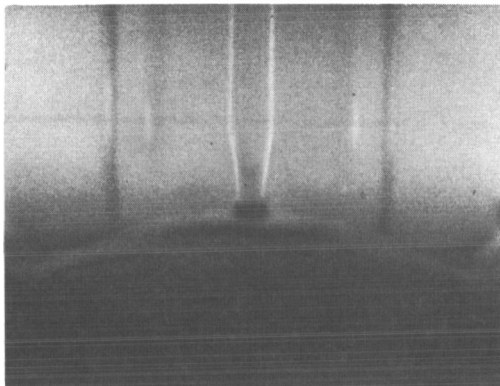
Figure 7. - Uncovering of liquid-vapor sensor in vertical upward orientation. Draining test in ethanol.



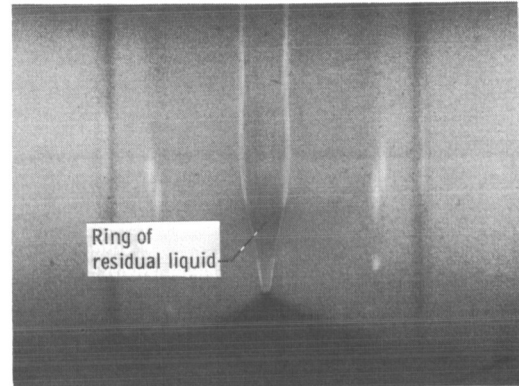
(a) Sensing tip 100 percent covered.



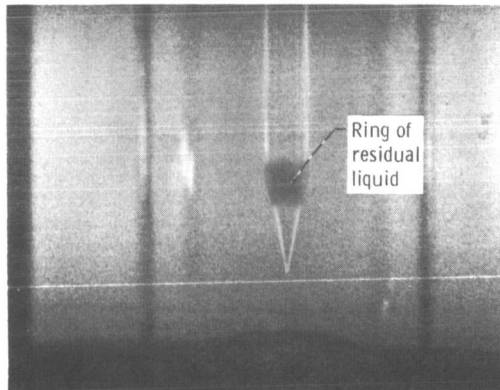
(b) Sensing tip 80 percent covered.



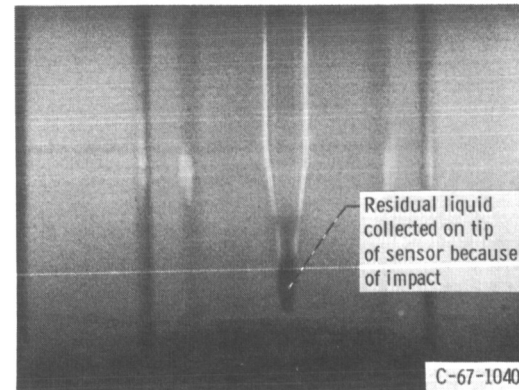
(c) Sensing tip 40 percent covered.



(d) Sensing tip 10 percent covered.



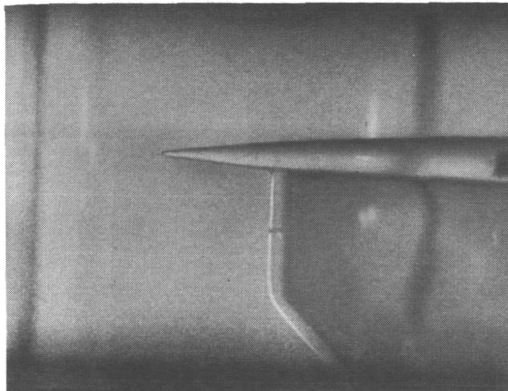
(e) Sensing tip free of liquid.



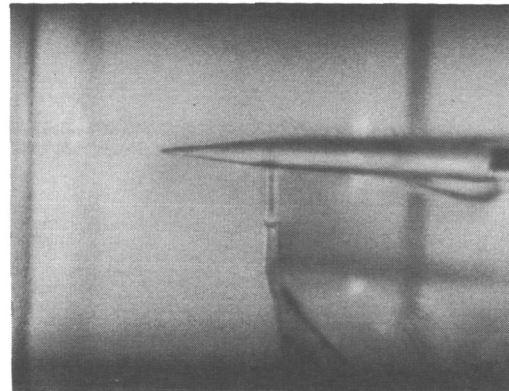
(f) Termination of drop.

Figure 8. - Uncovering of liquid-vapor sensor in vertical downward orientation. Draining test in ethanol.

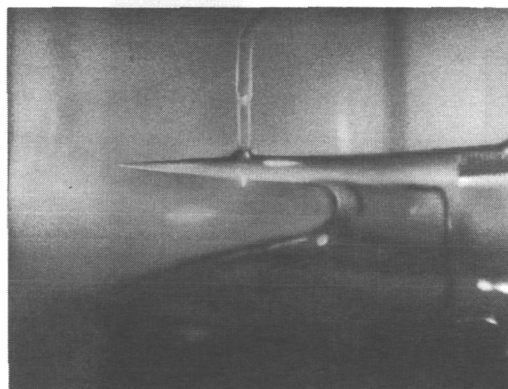
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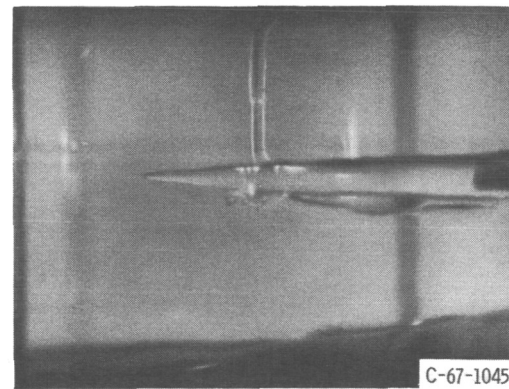
(a) Liquid collected between wire lead and sensor body.



(b) Sensing tip 100 percent uncovered. Breaking of residual film between wire lead and sensor body.



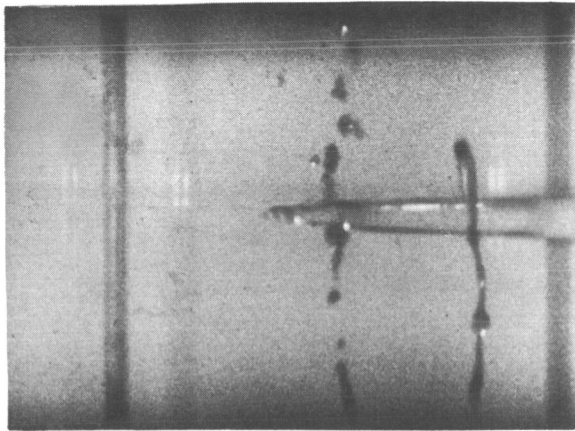
(c) Sensing tip 100 percent uncovered. No film formation between wire lead and sensor body.



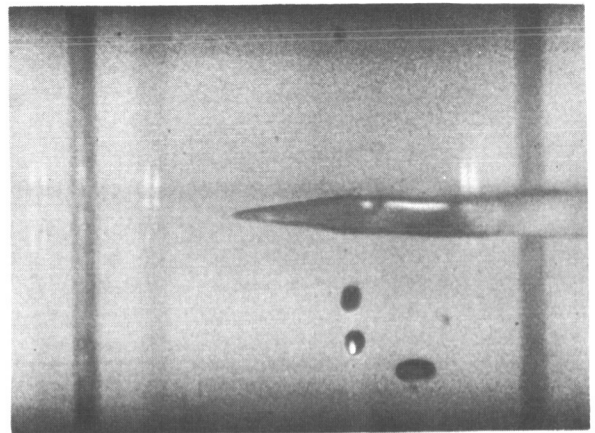
(d) Termination of drop; residual liquid falling from sensor body only.

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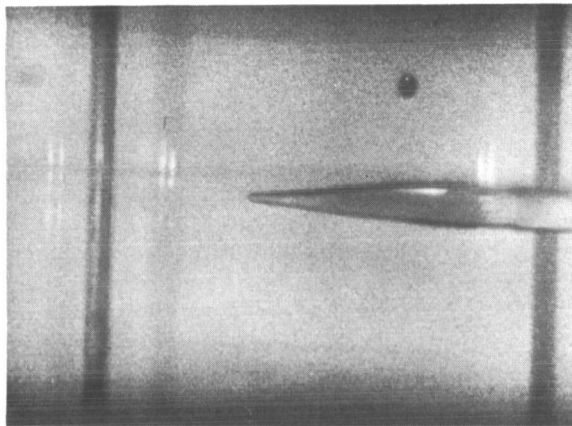
Figure 9. - Uncovering of temperature sensor with simulated wire lead in horizontal orientation. Draining tests in ethanol. Note difference in simulated wire lead orientation.



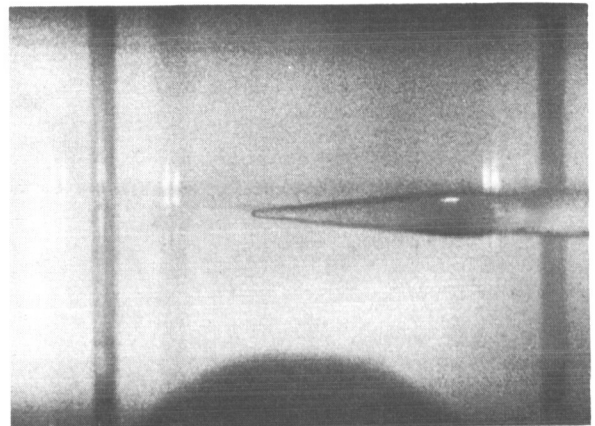
(a) Initial splash.



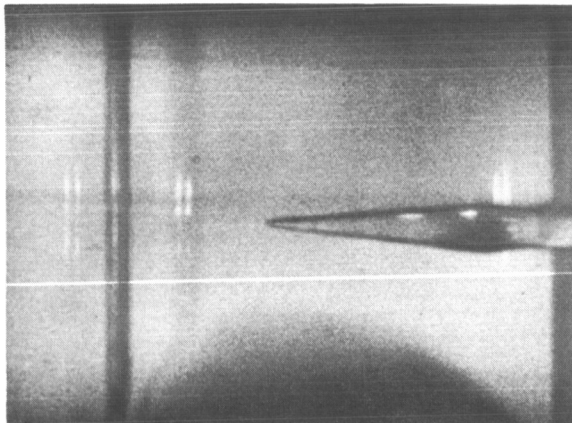
(b) Sensor 60 percent covered by liquid.



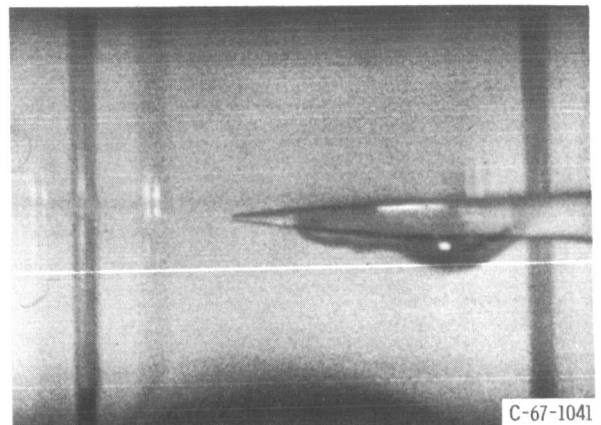
(c) Liquid ring forming.



(d) Liquid ring continuing to form.



(e) Liquid ring formed, clearing sensing tip.

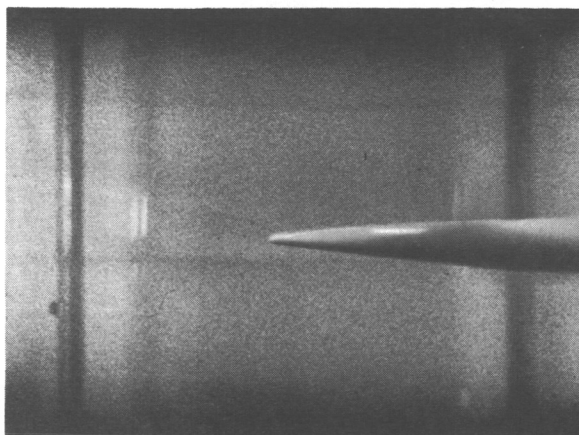


(f) Termination of drop; liquid falling from main body only because of impact.

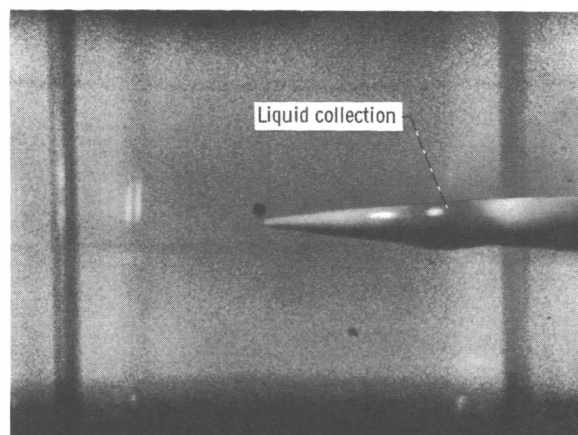
C-67-1041

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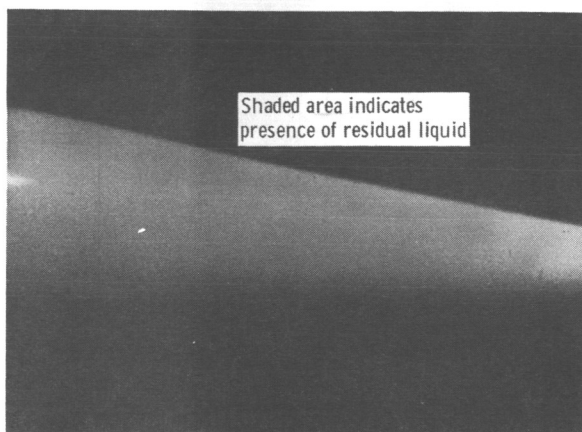
Figure 10. - Movement of Freon on temperature sensor in horizontal orientation. Splash test in Freon.



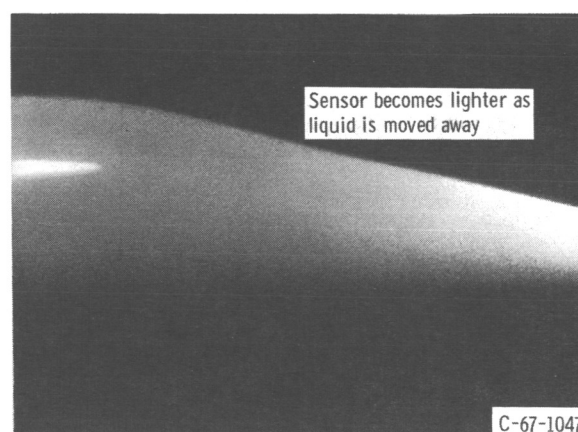
(a) Temperature sensor covered with residual liquid immediately after splash.



(b) Temperature sensor with liquid collected away from sensing tip.



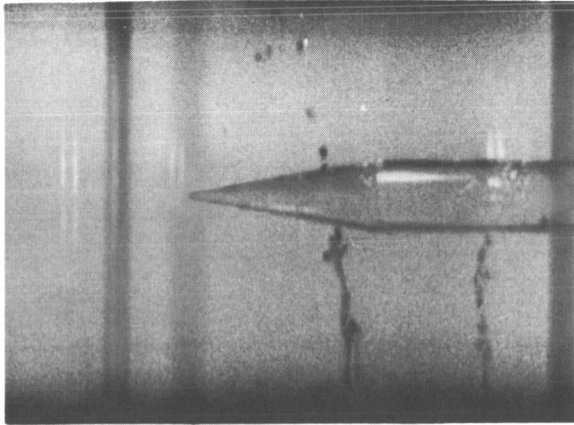
(c) Sensor evenly covered with residual liquid.



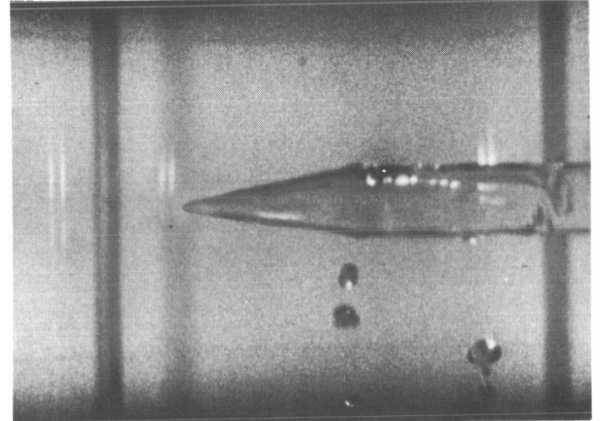
(d) Sensor tip after liquid-vapor had moved away.

Figure 11. - Uncovering of sensors in horizontal orientation. Splash tests in ethanol.

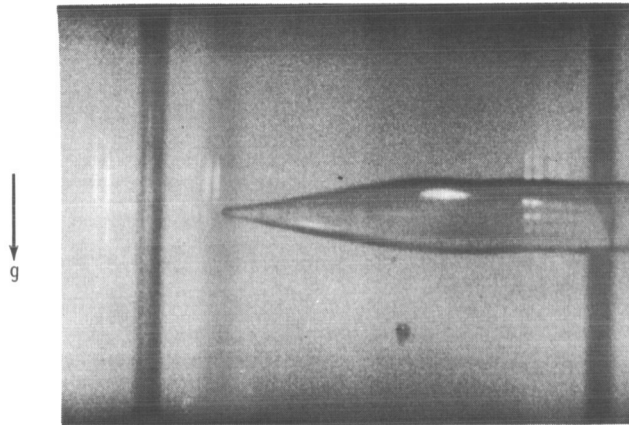




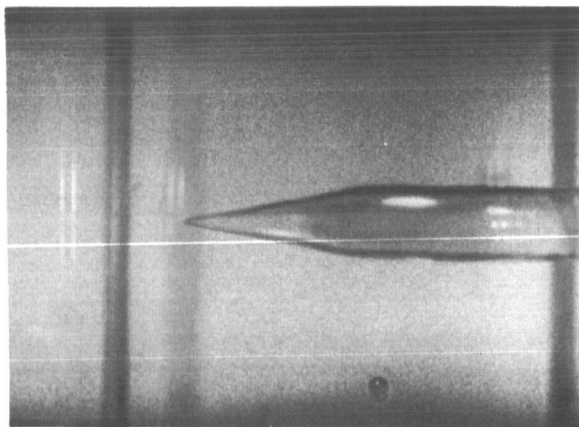
(a) Initial splash.



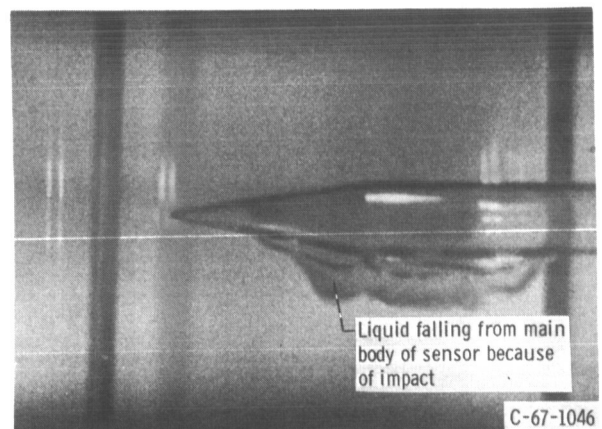
(b) Sensor 60 percent covered by liquid.



(c) Sensor 90 percent covered by liquid.



(d) Sensing tip free of liquid.



(e) Termination of drop.

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Figure 12. - Movement of Freon on liquid-vapor sensor in horizontal orientation. Splash test in Freon.

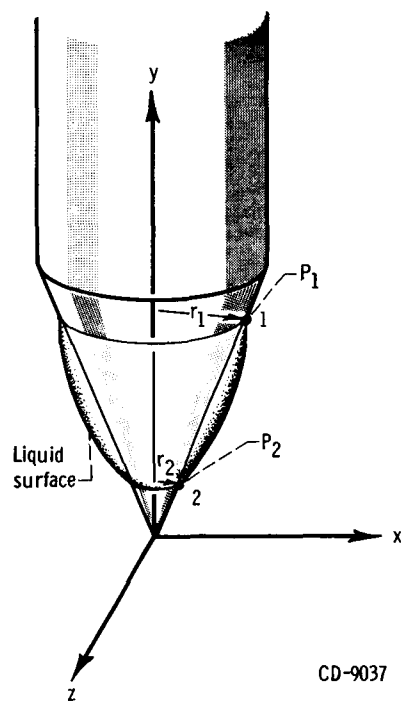


Figure 13. - Surface tension effects on conical object in low-gravity environment. Internal pressures,  $P_1$  and  $P_2$ ; radii at points 1 and 2,  $r_1$  and  $r_2$ ; external pressure,  $P_0$ .

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